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Effect of Concrete Moisture Conditions on the Adhesion of Conductive Paint

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Effect of Concrete Moisture Conditions on the

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Abstract:	One means of applying cathodic protection to reinforced concrete structures involves the use of conductive paint as an anode on the concrete surface. A concern associated with a trial conductive paint cathodic protection system installed and monitored by the Ontario Ministry of Transportation was the premature delamination of the conductive paint. The purpose of the investigation reported here was to identify the cause of adhesion failure of the conductive paint with special emphasis on the effect of moisture in the concrete upon the adhesion. Concrete test panels with and without reinforcement were prepared, then painted and exposed under a variety of moisture conditions. The reinforced concrete panels were powered at current densities typical of those encountered in the field. For the initial evaluation, a standard paint adhesion test that involved scoring and taping the paint surface was used to evaluate the amount of adhesion. Other tests which were used on selected panels included measurement of concrete moisture content, concrete surface acidity and copper-copper sulphate half cell electrical potentials. For concrete panels which were not powered, very little adhesion failure was observed. For concrete panels that were powered, delamination was observed in almost all cases. All failures involved deterioration of the concrete at the paint interface. It was observed that delamination of the paint appeared most likely to occur under conditions of high moisture and high chloride concentrations in the concrete. Recommendations include development of a convenient on-site test to monitor concrete moisture.
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Effect of Concrete Moisture Conditions

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1/ Executive Summary

This report presents the findings of an experimental investigation undertaken to identify the cause of delamination of a conductive paint from reinforced concrete at two MTO test sites for cathodic protection. Thorough attention was paid to various levels of moisture in the concrete and in the exposure environment. A secondary task was to investigate methods of monitoring moisture in concrete.

Twenty-four concrete panels without reinforcement were prepared, painted and exposed under a variety of conditions of either preparation or exposure, including exposure at the test sites. Seven panels of reinforced concrete were also prepared, painted, electrified and exposed to various moisture conditions.

The major test method used for all the panels was a standard paint adhesion test. Other tests which were used on selected panels included concrete moisture content, concrete surface acidity and copper-copper sulphate half cell electrical potentials. The paint itself was also examined for its weatherability and its morphology.

For the concrete panels which were not electrified,very little adhesional failure was observed. Good adhesion was attained under all exposure conditions including various humidity levels, flowing and static water, flowing and static brine, freezing and thawing and intensified sunlight.

For the concrete panels which were electrified, severe delamination was observed in almost all cases. These included panels exposed to stagnant brine, to stagnant water and simply to an outdoor environment. The only electrified panel for which failure was not severe was the laboratory control panel which was exposed to a relatively dry environment. The impressed current densities were well within the guidelines where the production of chlorine gas and hydrogen ions at the paint anode should not be occurring, but considerable evidence of their production at the paint-concrete interface was obtained.

It is concluded that the electrochemical process is causing the production of chlorine gas or hydrogen ions at the interface between the paint and the concrete and that these chemicals are acting either individually or together under moist conditions to degrade the concrete surface at the interface with the paint. When the concrete substrate for the paint deteriorates sufficiently, the paint delaminates.

When examined by electron microscopy, the paint appears to be a heterogeneous composite of irregular graphite particles held together by a minimum amount of resin binder. Weathering studies indicated that the paint itself had not seriously deteriorated at the MTO sites.

To be successful, the conductive paint system appears to require some improvement in the anode situation to dissipate the effects of these anode reactions.

A laboratory method to measure quantitatively the moisture content in concrete was developed. No convenient quantitative method of on-site monitoring of concrete moisture was found.

Also included in the report are new techniques which have been developed for on-site evaluation of paint adhesion and on-site evaluation of concrete surface acidity.

2/ Introduction and Background

Reinforced concrete is a widely used structural material for highway bridges, piers and parking garages. Under normal exposure and weathering the concrete offers a passive, non-corrosive environment for the steel reinforcing bars imbedded in the concrete. The passivity of concrete is believed to be greatly reduced, however, when chloride ions are present in the concrete. These ions can result from an environment of salt water or from the use of deicing salt in winter. When the iron in the reinforcing bar corrodes to form iron oxides, the iron oxides occupy a greater volume than the original iron. As the reinforcing bar tries to expand, tensile stresses are created in the concrete which lead to cracking and spalling, and an overall appearance of deterioration of the concrete structure. Repair of this damage is frequently performed by removing the outer portion of concrete, cleaning or replacing the reinforcing bar, applying a protective organic coating to the reinforcing bar and pouring a fresh top layer of concrete. This repair work is costly and inconvenient.

Methods are being considered to reduce or stop this corrosion of the steel reinforcing bars in concrete structures which have already been built. These methods include physical membranes to limit the migration of water and oxygen to the reinforcing bar, sealants and inhibitors to reduce the penetration of chloride ions, and cathodic protection to halt the corrosion process by electrochemical means. One method of cathodic protection involves the application of a conductive paint to the exposed concrete surfaces. The paint and reinforcing bar are connected electrically to an external DC power supply so that the paint is made the anode and a low current flows through the concrete between the paint and the reinforcing bar. The advantage of such a system is that it would be relatively simple, inexpensive and easy to retrofit to existing structures.

This cathodic protection system is one of several which have been chosen for further study by the Ministry of Transportation of Ontario(1). Field application and testing of the electrified paint system had been performed at sites at the Burlington Bay Skyway and at the Highway 401 overpass at Leslie Street in Toronto. At the Burlington site the paint system appeared to be satisfactory for about 12 months, after which the conductive paint was observed to be falling off in small spots. The condition became worse at longer times. At the Toronto site, severe delamination of the paint was observed after 3 to 6 months of operation. Photographs of the paint condition at the test sites are presented in Appendix A.

This experimental study was undertaken to investigate the cause or causes of the adhesional failure of the conductive paint with special emphasis on the effect of moisture in the concrete upon the

adhesion, with a view to making recommendations to enhance the adhesion under field conditions. Experimental variations were made in the conditions under which the paint was applied to unreinforced concrete , in the conditions to which the painted, unreinforced concrete was exposed and in the states of electrification and exposure of painted, reinforced concrete. The concrete under investigation had been poured into 18" x 18" panels, both with and without reinforcing bars. Details of the preparation of the panels and the electrochemical setups are given in Appendix B. The adhesion test procedure was an adaptation of ASTM D 3359-78, which is described in more detail in Appendix C. The moisture content in the concrete was varied qualitatively by varying the experimental conditions.

A secondary task was to investigate methods of monitoring moisture in concrete. A method for the quantitative determination of the moisture content in the concrete was developed, and is described in Appendix D.

The conductive paint used was a commercially available material containing a graphite filler and an acrylic binder suspended in an aromatic solvent. The morphology and weatherability of the dried paint are examined in detail in Appendix E.

In order to provide more information about the interface between the paint and the concrete, a qualitative test of the pH of the concrete at the interface was developed. The test and test results are presented in Appendix F.

In an attempt to monitor the effectiveness of the cathodic protection system, the copper-copper sulphate half-cell potentials were measured for the electrified panels according to ASTM test C 876-80. These results are given in Appendix G.

3/ Paint Adhesion Results and Observations

3.1/ Effects on Control Panels

In order to ascertain the effects of various experimental conditions on paint adhesion, it was necessary to prepare a number of control panels of painted concrete as references for comparison with panels for which the experimental conditions were being varied. In this subsection, the differences between the control panels are discussed.

3.1.1/ Time

The test for adhesion (ASTM D 3359-78) is a more severe test of painting system failure than visual observation of delamination. When replicate unreinforced panels of the standard concrete formulation were painted according to the manufacturer's recommendations and were exposed outdoors for up to nine months, only a small degree of deterioration could be observed by the test as recorded in Table 7.1.1. The standard test was modified in three ways: at one week, the panels were observed visually but were not scribed; during cold weather, the pressure-sensitive tape was not used because it would not stick to the paint surface; at nine months a full crosshatch scribing and tape pull was used. Adhesion for these control panels was still good after nine months of outdoor exposure.

3.1.2/ Salt Content

In order to simulate the effect of road salt on adhesion, sodium chloride was added to the concrete mixture during formulation of this panel. When this concrete was subsequently painted and exposed up to nine months in the laboratory, the adhesion was found to be very good at all times, as can be seen in Table 7.1.2. This exposure condition in the laboratory would be less severe than outdoors. As a control panel it serves as a reference for other panels studied under various simulated environmental conditions.

3.1.3/ Outdoor Exposure

In order to compare the exposure conditions and paint adhesion performance at the two MTO sites, at the Waterloo exposure site and under laboratory conditions, replicate panels were exposed and monitored at all the outdoor sites. The results are given in Table 7.1.3. All panels were observed to have good adhesion throughout the test period of at least seven months. No significant differences could be observed among any of the outdoor exposure sites nor between the outdoor

panels and the laboratory control panel. One of the outdoor exposure panels at the Toronto site had been placed at an angle under the overpass in the direct path of an appreciable run-off of rainwater and brine and did not show any loss of adhesion.

3.1.4/ Salt Content and Outdoor Exposure

The salt content for some unreinforced panels was raised as high as 10 lb. of chloride ion per cubic yard of concrete. As can be seen in Table 7.1.4, one of the two replicate panels given outdoor exposure started to show slight deterioration in its adhesion after about three months' exposure at the Waterloo site.

3.1.5/ Electrification and Salt Content

In order to establish a reference for electrified panels, a reinforced concrete panel was constructed in the standard manner described earlier and electrified in the laboratory at an average impressed current density of 1.0 mA per ft^2. The adhesion was observed to show slight deterioration at eight weeks compared to panels which had not been electrified (Table 7.1.5). Severe deterioration was not observed even after eight months' operation but the adhesion was not as good as that observed for panels which were not electrified under similar exposure conditions.

3.2/ Effects of Application Conditions

In this subsection, attention is paid to the conditions under which the paint is applied to the concrete, specifically the conditions of the concrete, the preparation of the concrete surface and the application of the paint. After painting, all panels were given similar outdoor exposures at the Waterloo site.

3.2.1/ Concrete Moisture Conditions

Since application of the paint to bridges in the field could occur under a variety of ambient moisture conditions, it was important to examine the effect on adhesion of moisture in the concrete at the time of application of the paint. Concrete panels were conditioned for five days prior to painting in environments of different moisture levels as reported in Table 7.2.1. The control panels experienced an environment of 30-50% relative humidity, two panels experienced a humid environment of 55-85% relative humidity, and the immersion panels were soaked for five days and then allowed to dry on the surface before painting. After outdoor exposure, adhesion was observed to be good for the panels conditioned in the different environments, but for the immersed

panels, one of the replicates showed poor adhesion shortly after painting and the other replicate showed deterioration in the adhesion after outdoor exposure for eight weeks.

3.2.2/ Concrete Temperature

Since field application of the paint could occur under a variety of ambient temperatures, the effect of the temperature of the concrete at the time of application on the resulting adhesion was studied. In order to simulate painting at low temperature, two panels (along with the paint) were refrigerated at 5°C for four days prior to painting. To simulate high temperatures, two others were held at 35-40°C for 4 days prior to painting. All panels, including the control panels at room temperature, showed good adhesion throughout the exposure period (Table 7.2.2).

3.2.3/ Concrete Surface Treatments

Several treatments of the concrete surface are possible during field application of the paint. All panels were sandblasted, since this treatment would be necessary in any field application to existing concrete structures in order to remove dirt and other contamination which may collect on the concrete surface. As can be seen in Table 7.2.3, two panels were not given any further treatment, two were water-washed, two were air-blown and two were both air-blown and flamed. After painting and outdoor exposure all panels appeared to show satisfactory adhesion up to nine months with the possible exception of one of the panels which was not air-blown for which the adhesion was marginal.

3.2.4/ Paint Thickness

Another field application variable which was investigated in this study of adhesion was the thickness of the applied paint. The paint manufacturer specified a minimum dry film thickness of 0.015 in. Replicate panels having dry film thicknesses in the ranges of 0.016 in. to 0.023 in. and 0.028 in. to 0.040 in. were prepared in the laboratory and exposed outdoors. As shown in Table 7.2.4, adhesion was satisfactory up to nine months after application with the possible exception of one of the thickly painted panels for which the adhesion at nine months was marginal.

3.3/ Effects of Exposure Conditions

In this subsection, the environmental conditions to which the painted concrete was exposed are examined as possible causes of the paint system failure. The conditioning, preparation and paint application were the same for all the panels.

3.3.1/ Moisture

These painted panels were subjected to exposure environments of different humidity levels for an extended period of time. The control panels were exposed in the laboratory and outdoors at the Waterloo site. As reported in Table 7.3.1, one panel was exposed to a high humidity environment, one was exposed to a dripping flow of water on alternate days, and one was exposed to a static pond of water on alternate days. All panels showed very good adhesion throughout the exposure period of nine months.

3.3.2/ Brine

The effect of de-icing salt in runoff water was examined by exposing one painted concrete panel to a dripping flow of brine on alternate days and another panel to a static pond of brine on alternate days. After exposure for nine months the panels showed good adhesion, as can be seen in Table 7.3.2. Selected photographs follow this table, providing a visual comparison of the three panels after long term exposure.

3.3.3/ Freezing and Thawing

Under field exposure conditions painted concrete would undergo freezing and thawing. In order to isolate and intensify any effect which this phase change of moisture in the system might have on the adhesion of the paint to the concrete, a painted concrete panel was frozen every third day for nine months. As can be seen in Table 7.3.3, the adhesion of the paint was very good throughout this period.

3.3.4/ Sunlight

In order to isolate and intensify any effect which sunlight might have on the adhesion of the paint to concrete, a painted concrete panel was exposed to a sunlamp for 23 hours per day. As reported in Table 7.3.4, the adhesion of the paint to the concrete remained good throughout the exposure period of nine months.

3.4/ Effects on Electrically Powered Panels

Since the paint failure at the test sites occurred during the operation of the impressed current cathodic protection systems, the experiments in this subsection were performed to determine whether the cathodic protection system was contributing to the paint failure.

3.4.1/ Outdoor Exposure

A reinforced concrete panel was exposed at the outdoor Waterloo exposure site and electrified at an average impressed current density of 1.0 mA per ft^2. The results are shown in Table 7.4.1 and are compared to the indoors control panel. The adhesion of the paint showed severe deterioration by four weeks and the paint was observed to flake off the concrete. The loss of adhesion was much more severe than the deterioration which was observed for the control panel exposed in the laboratory at the same current density.

The flakes of paint which lifted off showed aggregate adhering to the underside. This observation indicates that the cement binder had deteriorated near the paint surface to such an extent that the aggregate was no longer held together. The concrete which had been exposed by the removal of the paint was crumbly in nature.

3.4.2/ Moisture Conditions

The adhesion of the paint to electrified reinforced concrete was observed under various moisture exposure conditions. For the same average current density, the control panel was exposed to laboratory conditions, one panel was exposed outdoors at the Waterloo site, and one panel was subjected to a static pond of water on alternate days. As recorded in Table 7.4.2, the adhesion of the electrified panels exposed outdoors or to a static pond of water deteriorated much more quickly than the adhesion of the electrified control panel. A slight smell of chlorine gas was observed for the panel with the pond of water. This panel had been placed horizontally and had a high rim around the pond which would help collect the dense gas.

3.4.3/ Brine Exposure

The adhesion was monitored for an electrified panel which was exposed on alternate days to a static pond of brine. The adhesion results are presented with those for a water pond and for the control panel at the same average current densities in Table 7.4.3. It is seen that the adhesion fails quickly in this system similar to the water pond reported in the preceding section. A slight smell of chlorine gas could also be observed.

3.4.4/ Current Density and Outdoor Exposure

A second painted panel of reinforced concrete was exposed outdoors at the Waterloo site and electrified at an average impressed current density of 5.0 mA/ft^2. As can be seen from Table 7.4.4,

this panel failed within four weeks of its initial exposure as had the panel at 1.0 mA/ft^2. Its failure was even more severe than that of the panel at 1.0 mA/ft^2. When the paint was scribed for the tape adhesion test, all the paint flaked off in the scribed region so that the need for any tape was eliminated.

3.4.5/ Current Density and Water Exposure

A second painted panel of reinforced concrete was exposed to a water pond on alternate days and electrified at 5.0 mA/ft^2. As recorded in Table 7.4.5, the adhesion of this panel failed even more drastically than that of the panel at 1.0 mA/ft^2. The failure was more severe on the side of the panel for which the chloride concentration was lower. A strong smell of chlorine gas was observed at this current density.

3.4.6/ Current Density and Brine Exposure

A second painted panel of reinforced concrete was exposed to a brine pond and electrified at 5.0 mA/ft^2. The adhesion of this panel is compared to that of the panel with the brine pond at 1.0 mA/ft^2 in Table 7.4.6. At the higher current density, the adhesion failed even more dramatically. No smell of chlorine gas was observed, however.

4/ Discussion

4.1/ Paint Application Conditions

The paint as it is being applied is an organic liquid suspension of low surface energy, while the prepared concrete substrate is a rough inorganic solid of appreciably higher surface energy. As a result, the thermodynamic and capillary driving forces for wetting are very favourable, and thorough, intimate coverage of the concrete is to be expected.

For the panels which had not been electrified, it was found that the paint could be applied successfully under a wide variety of conditions, including various salt concentrations in the concrete substrate, various moisture levels in the concrete substrate, various temperatures of the concrete substrate, various cleaning procedures for the concrete and various paint thicknesses. The only conditions under which the adhesion became questionable were those of high salt content, of extremely high humidity, of surface preparation by sandblasting when the grit was not removed, and of coating thicknesses much greater than specified by the manufacturer. In the case of concrete with a high salt content, some sand appeared attached to the interfacial surface of the paint which was removed, indicating that at least partial failure was occurring in the surface of the concrete near the interface. In the case of high humidity, the paint may be wetting the moisture on the concrete rather than the concrete itself. In the case of improper removal of grit, the paint may be wetting the grit rather than the concrete. In the case of the thick coatings, fracture may be occurring under test conditions within the paint itself due to the brittle nature of the paint as discussed in Appendix E. The possible failure with concretes having a high salt content is of concern since the salt content cannot be easily reduced in existing concrete structures. The conditions of humidity, surface preparation and paint thickness can be controlled readily during field applications and were likely controlled during the applications at the test sites.

4.2/ Paint Exposure Conditions

The performance of a paint system under long term exposure without electrification is the result of any long term chemical interactions between paint and substrate, the interaction of weather elements with the paint and the substrate, and the degree of protection afforded the substrate by the paint. Chemically, the paint is reasonably inert towards the concrete because the graphite is unreactive and the acrylic binder has very little in the way of reactive groups. There is a small concern that the highly alkaline concrete may catalyze the de-esterification of the ester groups in the

acrylic binder. In the detailed study of the weathered paint in Appendix E, however, there was no evidence of any deterioration of the paint binder.

From the composition of the paint, it should be reasonably stable towards weather elements. Acrylics weather well and are a frequent binder for residential and automotive exterior paints. Graphite is chemically inert and provides an opaque barrier to the penetration of ultraviolet light through to the paint interface with the substrate. The paint did appear somewhat porous under microscopic examination in Appendix E, but it should also be mentioned that at the Burlington site, one section of graphite paint had been topcoated with house paint. This topcoated section failed by about the same extent as the section which had not been topcoated, indicating that the paint failure at the site could not be attributed to any inability of the conductive paint to protect the substrate.

For the panels which had not been electrified, it was found that the painted panels successfully withstood a wide variety of weathering conditions including outdoor exposures at three different locations and intensified exposure to high humidity, high ultraviolet light, frequent freezing and thawing, static ponds of water and brine and dripping flows of water and brine. The only unelectrified panel which failed under exposure conditions after having been painted according to the manufacturer's specifications was one of the two panels which used a concrete mix with a high chloride ion concentration which has already been discussed in subsection 4.1. These results indicate that failure at the test sites cannot be attributed to the effect of the exposure conditions on the paint unless the initial concretes had high salt contents.

4.3/ Electrification of the Painted Concrete

When the reinforced concrete panels in this study were electrified under moist conditions, early failure of the painting system was experienced. Since the panels which had not been electrified under similar conditions did not fail, the electrification appears to be the major cause of the paint system failure.

The electrochemical mechanisms of the corrosion and the cathodic protection of steel reinforcing bars imbedded in concrete are complex and outside the scope of this project. A few very simplistic mechanistic reactions can be postulated to act as guidelines to a preliminary understanding of the electrochemical processes occurring.

Without electrification, spontaneous corrosion of the iron reinforcing bar in the presence of water can be thought of as occurring by the following reactions:

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e$

Cathodic reaction: $H^+ + e \rightarrow H^o$

$H^o + H^o \rightarrow H_2$ gas

or $1/2\ O_2 + H_2O + 2e \rightarrow 2OH^-$ with oxygen present

The anodic and cathodic reactions would probably occur at different sites on the steel bar which would act as the conductor for the electrons. Ions would flow through the water, completing the electrical circuit. Corrosion proceeds when both reactions occur simultaneously. In the presence of oxygen various oxides of iron would also form, including higher oxidation states.

For cathodic protection, only the cathodic reactions are allowed to occur at the steel bar and the anodic reaction is designed to occur elsewhere in the system. Electrical current flows by electrons through the wire connecting the electrodes and predominantly by ions through the medium between the electrodes. In the present study an external DC power supply is used to impress the anodic or positive polarity on the paint and the cathodic or negative polarity on the steel reinforcing bar to such an extent that a predetermined electrical current is flowing in the system, specifically 1 or 5 mA/ft^2. The ion flow in the concrete would be such that cations such as H+ and Na+ would be attracted towards the steel cathode, and anions such as OH- and Cl- would be attracted towards the paint anode.

At the iron cathode, the predominant reaction becomes the generation of hydrogen gas:

$H^+ + e \rightarrow H^o$

$Ho + Ho \rightarrow H_2$ gas

or $1/2\ O_2 + H_2O + 2e \rightarrow 2OH^-$

In other words, the iron no longer corrodes and is protected. Hopefully, the hydrogen gas will diffuse out of the system and do no damage.

At the anode, since the graphite paint is inert, two possible reactions could occur, the generation of chlorine gas and the generation of oxygen gas:

1. $Cl^- - e \quad Cl^o$

   $Cl^o + Cl^o \rightarrow Cl_2$ gas

2. $2OH^- - 2e \quad H_2O + O^o$

   $O^o + O^o \quad O_2$ gas

Furthermore, if the second reaction predominates, it would diminish the concentration of hydroxyl ions in the concrete in the vicinity of the anode paint. Since water in the system is present predominantly in the molecular form rather than in ions and since an equilibrium exists between hydroxyl ions and hydrogen ions, any diminution in the hydroxyl ion concentration would be accompanied by a corresponding increase in the hydrogen ion concentration. In other words, the acidity level in the concrete near the anode would increase.

Using this simple model, calculations can be made to show that for the production of chlorine gas at a current density of 1 mA/ft^2, the gas would be produced at a rate of about 10mL per square foot of anode per day. For oxygen, the number would be 5mL per square foot of anode per day. Increasing the current density by a factor of 5 would increase the gas production rates by a factor of 5.

In the current study, all the failures involved a deterioration of the concrete at the paint interface. This failure indicates that a destructive chemical reaction is occurring in the concrete at the vicinity of the anode. Evidence of both types of anodic reactions have been found even though the current density was kept well below the guide of 10 mA/ft^2 reported to prevent the formation of chlorine gas or acid at the anode(2). A strong odour of chlorine gas was detected in the ponded panels. A hundred-fold increase in the acidity of the concrete near the interface on failed panels was also observed. Either reaction could bring about the destruction of the concrete at the interface. To be detrimental to the concrete, it is thought that the pH of the medium should be below 7(3), whereas the lowest pH observed in the study in Appendix F was 8.5. On the other hand, chlorine gas is known to be destructive to concrete, particularly when moist(4). Atomic chlorine is particularly reactive. This difference between moist and dry conditions in the reactivity of chlorine gas with concrete could explain the observation in this study that the electrified control panel under relatively dry conditions did not fail to the same extent as the other electrified panels, and the site observation that the failure at the Burlington site was not as rapid or as extensive as the failure at the Toronto site.

It appears, then, that the conductive paint system is most likely to fail under the conditions where cathodic protection is most needed, that is conditions of high moisture and high chloride concentrations in the concrete. There are some possible remedies such as fluoride treatments of the concrete surface, paint primers and paint porosity which could be investigated but are outside the scope of this project.

5/ Conclusions

5.1 The major cause of the delamination of the conductive paint is the electrochemical process.

5.2 The delamination of the paint is a result of the destruction of the concrete at its boundary layer at the interface between the paint and the concrete.

5.3 The destruction of the concrete is a result of the electrochemical reactions occurring at the paint anode.

5.4 The destruction of the concrete is aggravated by the presence of moisture in the concrete and its environment.

5.5 Without the operation of the cathodic protection system, the paint adheres well to the concrete under nearly all conditions when applied according to the manufacturer's specifications. The exceptions would be very high moisture conditions and very high chloride content in the concrete.

6/ Recommendations

6.1 Modifications to the cathodic protection system should be made to ensure satisfactory adhesion of the conductive paint.

6.2 More information should be obtained on electrochemical reactions occurring at an inert anode in contact with concrete.

6.3 Modifications to eliminate or diminish the destructive effects of electrochemical reactions at the anode should be sought and evaluated.

7/ Tabulated Results

TABLE 7.1.1: Effect of Time on Adhesion of Control Panels

Sample	(Cl^-), lb/yd³	Exposure	1 week	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1	0	outdoors	VG	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2	0	outdoors	VG	VG	VG	VG	VG	VG	VG	VG	G	G

Legend for Adhesion Tests (modified ASTM D3359-78)

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.1.2: Effect of Salt Content of Adhesion of Control Panels

Sample	(Cl^-), lb/yd³	Exposure	1 week	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1	0	outdoors	VG	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2	0	outdoors	VG	VG	VG	VG	VG	VG	VG	VG	G	G
3	5	laboratory	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG

E Excellent
VG Very Good
G Good
P Poor (failure)

(Cl^-) added to original mixture as sodium chloride

TABLE 7.1.3: Effect of Outdoor Exposure on Adhesion of Control Panels

Sample	(Cl^-), lb/yd³	Exposure	1 week	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1	0	Outdoors, Waterloo	VG	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2	0	"	VG	VG	VG	VG	VG	VG	VG	VG	G	G
3	5	Laboratory	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
4	5	Outdoors, Waterloo	VG	VG	E	E/VG	VG	VG	VG	VG	VG	VG
5	5	"	VG	E	E	VG	VG	VG	VG	VG	VG	VG
6	5	Outdoors, Burlington	VG	-	VG	-	-	-	-	VG/G	-	7 mos E
7	5	"	VG	-	VG	-	-	-	-	VG/G	-	E
8	5	Outdoors, Toronto	VG	-	VG	-	-	-	-	VG/G	-	VG
9	5	"	VG	-	VG	-	-	-	-	E	-	VG

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.1.4: Effect of Salt Content and Outdoor Exposure on Adhesion of Control Panels

Sample	(Cl^-), lb/yd³	Exposure	1 week	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1	0	Outdoors	VG	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2	0	Outdoors	VG	VG	VG	VG	VG	VG	VG	VG	G	G
3	5	Laboratory	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
4	10	Outdoors	VG	G	G	VG/G	VG/G	VG/G	G	G/P	G/P	G/P
5	10	Outdoors	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G	G	G

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.1.5: Effect of Electrification and Salt Content on Adhesion of Control Panels

Sample	(Cl^-), lb/yd³	Current mA/ft²	Exposure	1 week	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1	0	-	outdoors	VG	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2	0	-	outdoors	VG	VG	VG	VG	VG	VG	VG	VG	G	G
3	5	-	laboratory	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
													8 mos
4	5	1.0	laboratory	-	-	VG	-	G/P	-	G/P	G/P	-	G/P
5	12	1.0	laboratory	-	-	VG	-	G/P	-	G/P	G/P	-	G/P

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.2.1: Effect of Concrete Moisture at Application on Adhesion

Sample No.	Conditioning Before Painting	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 mos	5 mos	9 mos
1 (control)	5 days, 30-50% R.H.	VG	VG	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
2 (control)	5 days, 30-50% R.H.	VG	VG	VG	VG	VG	VG	VG	G	G
3	5 days, 55-85% R.H.	VG	VG	E/VG	VG	VG	VG	VG	VG	VG
4	5 days, 55-85% R.H.	VG	VG	VG	VG	VG	VG	VG	G	G
5	5 days immersion	P	P	G/P	P	P	P	P	P	P
6	5 days immersion	G	G	G	G/P	G/P	G/P	G/P	G/P	G/P

E Excellent
VG Very Good
G Good
P Poor (failure)

Outdoor exposure
No chloride

TABLE 7.2.2: Effect of Concrete Temperature at Application on Adhesion

Sample No.	Conditioning Before Painting	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1	5°C (4 days)	VG	VG	VG	VG	VG	VG	VG
2	5°C (4 days)	E	VG	E/VG	VG	VG	VG	VG
3 (control)	23°C (5 days)	VG	VG	VG	VG	VG/G	VG/G	VG/G
4 (control)	23°C (5 days)	VG	VG	VG	VG	VG	VG	G
5	35-40°C (4 days)	VG	VG	VG	VG	VG	VG	VG
6	35-40°C (4 days)	E	E	E/VG	VG	VG	VG	VG

E Excellent
VG Very Good
G Good
P Poor (failure)

Outdoor exposure
No chloride

TABLE 7.2.3: Effect of Concrete Surface Treatments at Application on Adhesion

Sample No.	Treatment	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	sandblasted, air-blown	VG	VG	VG	VG	VG/G	VG/G	VG/G
2 (control)	sandblasted, air-blown	VG	VG	VG	VG	VG	VG	G
3	sandblasted, not air-blown	VG	VG	VG	VG/G	VG/G	VG/G	VG/G
4	sandblasted, not air-blown	VG	VG	VG	VG	VG	VG	G/P
5	sandblasted, water-washed	VG	VG	VG	VG	VG	VG	VG/G
6	sandblasted, water-washed	VG	VG	VG	VG	VG	VG	VG/G
7	sandblasted, air-blown, flamed	VG	V	G	VG	VG	VG	VG/G
8	sandblasted, air-blown, flamed	VG	VG	VG	VG	VG	VG	VG/G

E Excellent
VG Very Good
G Good
P Poor (failure)

Outdoor exposure
No chloride

TABLE 7.2.4: Effect of Paint Thickness on Adhesion

Sample No.	Thickness, x 10^{-3} in.	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	16-23	VG	VG	VG	VG	VG/G	VG/G	VG/G
2 (control)	16-23	VG	VG	VG	VG	VG	VG	G
3	28-40	E	E/VG	VG	VG/G	VG	VG	G
4	28-40	VG	VG	E	VG	VG	VG	G/P

E Excellent
VG Very Good
G Good
P Poor (failure)

Outdoor exposure
No chloride

TABLE 7.3.1: Effect of Moisture Exposure on Adhesion

Sample No.	Exposure	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	laboratory	VG	VG	VG	VG	VG	VG	VG
2 (control)	outdoors	VG	E	E/VG	VG	VG	VG	VG
3 (control)	outdoors	E	E	VG	VG	VG	VG	VG
4	55-85% R.H.	VG	VG	VG	VG	VG	VG	VG
5	water drip	VG	VG	VG	VG	VG	VG	VG
6	water pond	VG	VG	VG	VG	VG	VG	VG

E Excellent
VG Very Good
G Good
P Poor (failure)

(Cl^-), 5lb/yd^3

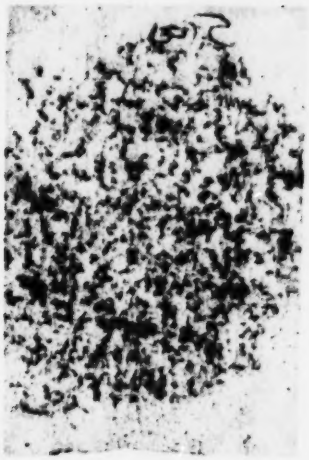
TABLE 7.3.2: Effect of Brine Exposure on Adhesion

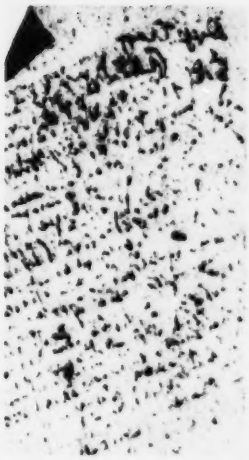
Sample No.	Exposure	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	laboratory (salt-free)	VG	VG	VG	VG	VG	VG	VG
2	brine drip	VG	VG	VG	VG	VG	VG	VG
3	brine pond	VG	VG	VG	VG	VG	VG	G

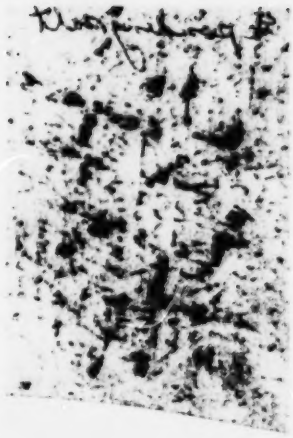
E Excellent
VG Very Good
G Good
P Poor (failure)

Brine was 5% sodium chloride in water

Table 7.3.2 Cont.







Exposure:

Laboratory | Brine drip | Brine pond

TABLE 7.3.3: Effect of Freezing and Thawing on Adhesion

Sample No.	Exposure	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	laboratory	VG	VG	VG	VG	VG	VG	VG
2	frozen (-3°C) every third day	VG	VG	VG	VG	VG	VG	VG

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.3.4: Effect of Sunlight on Adhesion

Sample No.	Exposure	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	4 mos	9 mos
1 (control)	laboratory	VG	VG	VG	VG	VG	VG	VG
2	sunlamp, 23 hrs/day	VG	VG	VG	VG	VG	VG	G

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.4.1: Effect of Outdoor Exposure on Electrically Powered Panels

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	outdoors	P	P	P	-	P
4	12	1.0	outdoors	P	P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.4.2: Effect of Moisture Conditions on Electrically Powered Panels

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	outdoors	P	P	P	-	P
4	12	1.0	outdoors	P	P	P	-	P
5	5	1.0	water pond	P	P	P	-	P
6	12	1.0	water pond	G/P	G/P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.4.3: Effect of Brine Exposure on Electrically Powered Panels

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	pond, water only	P	P	P	-	P
4	12	1.0	pond, water only	G/P	G/P	P	-	P
5	5	1.0	pond, brine	G/P	P	P	-	P
6	12	1.0	pond, brine	G/P	P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

Brine was 5% sodium chloride in water

TABLE 7.4.4: Effect of Current Density and Outdoors Exposure

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	outdoors	P	P	P	-	P
4	12	1.0	outdoors	P	P	P	-	P
5	5	5.0	outdoors	P	P	P	-	P
6	12	5.0	outdoors	P	P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.4.5: Effect of Current Density and Water Exposure

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	water pond	P	P	P	-	P
4	12	1.0	water pond	G/P	G/P	P	-	P
5	5	5.0	water pond	P	P	P	-	P
6	12	5.0	water pond	P	P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

TABLE 7.4.6: Effect of Current Density and Brine Exposure

Sample	(Cl^-), lb/yd³	Current, mA/ft²	Exposure	4 weeks	8 weeks	12 weeks	4 mos	8 mos
1 (control)	5	1.0	laboratory	VG	G/P	G/P	G/P	G/P
2 (control)	12	1.0	laboratory	VG	G/P	G/P	G/P	G/P
3	5	1.0	brine pond	G/P	P	P	-	P
4	12	1.0	brine pond	G/P	P	P	-	P
5	5	5.0	brine pond	P	P	P	-	P
6	12	5.0	brine pond	P	P	P	-	P

E Excellent
VG Very Good
G Good
P Poor (failure)

Appendix A/ Site Inspections

The Burlington and Toronto sites were visited with MTO personnel before finalizing the experimental plan and during the testing phase to monitor the test samples. Each site had been powered at an average current density of about 1 mA/ft^2 but was no longer being powered during this study.

Burlington Site

The Burlington test area was about 10 feet above the ground on a concrete pillar. A photograph of the south side of the pillar is shown in Figure A1. The paint can be seen to have delaminated in small areas, particularly in the top section. The bare spot in the centre of each section and the small regular spots near the electrodes are part of other tests performed by MTO and should be ignored when considering the paint condition. Inspection of this site was limited to visual observation. In Figure A2, the conductive paint has been topcoated with a residential paint. The failure is seen to be of equal severity and to be occurring at the interface between the conductive paint and the concrete.

Toronto Site

The Toronto site was a horizontal concrete beam and two supporting columns as can be seen in Figure A3. The delamination is seen to be occurring in large sheets. A closer photograph in Figure A4 shows that in the failed areas the paint is lifting cleanly from the concrete surface. When the exposed concrete areas were scored with a knife, in many cases, the concrete was sandy and crumbly. In many areas, the paint could be easily lifted with a knife or spatula.

The adhesion test was performed at the Toronto site on the east and west sides of the beam and on a pillar near and opposite its anode. The tape samples are shown in Figure A5. The adhesion is poor on both sides of the beam and on the pillar near the anode. The failure observed on the west side of the beam is extensive, corresponding to visual observation of extensive failure. It should be noted that fine aggregate is attached to the paint surface removed from the paint/concrete interface.

Paint samples were taken for a study of the weatherability and for a microscopic examination of the morphology of the dried paint, which are reported in Appendix E.

During the course of this investigation, a method was developed for determining the pH of the concrete at the interface. This method was applied to freshly exposed concrete at the Toronto site. The new method and results are given in Appendix F.

Figure A1/ Burlington Test Site. South Face

Figure A2/ Burlington Test Site. East Face

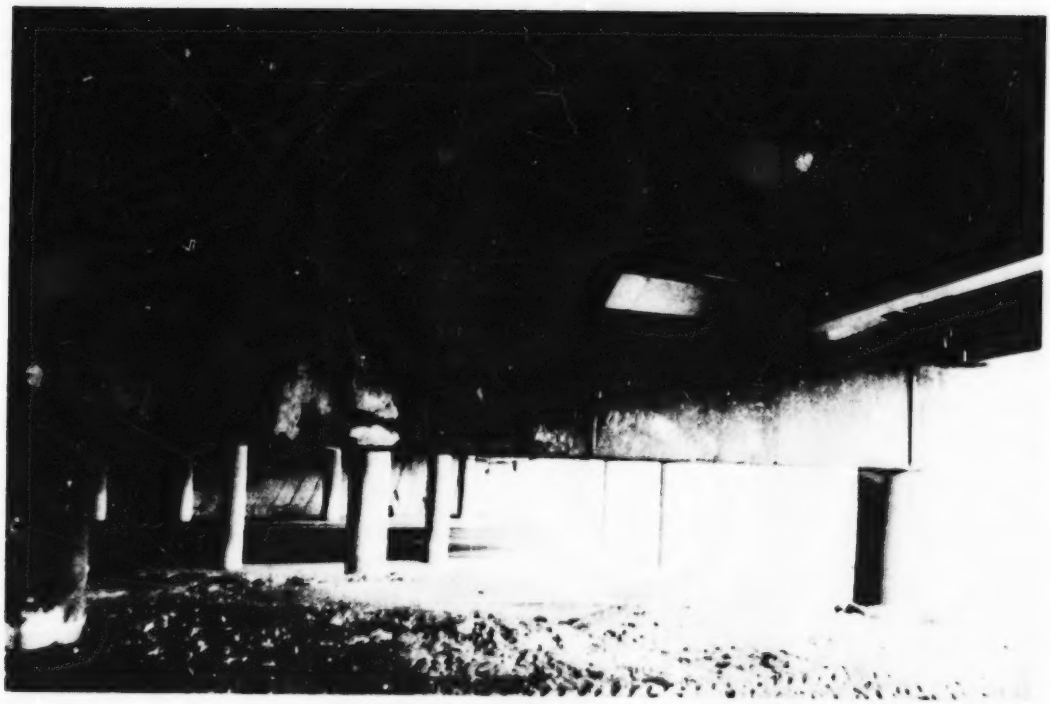


Figure A3/ Toronto Test Site. West Face of Beam

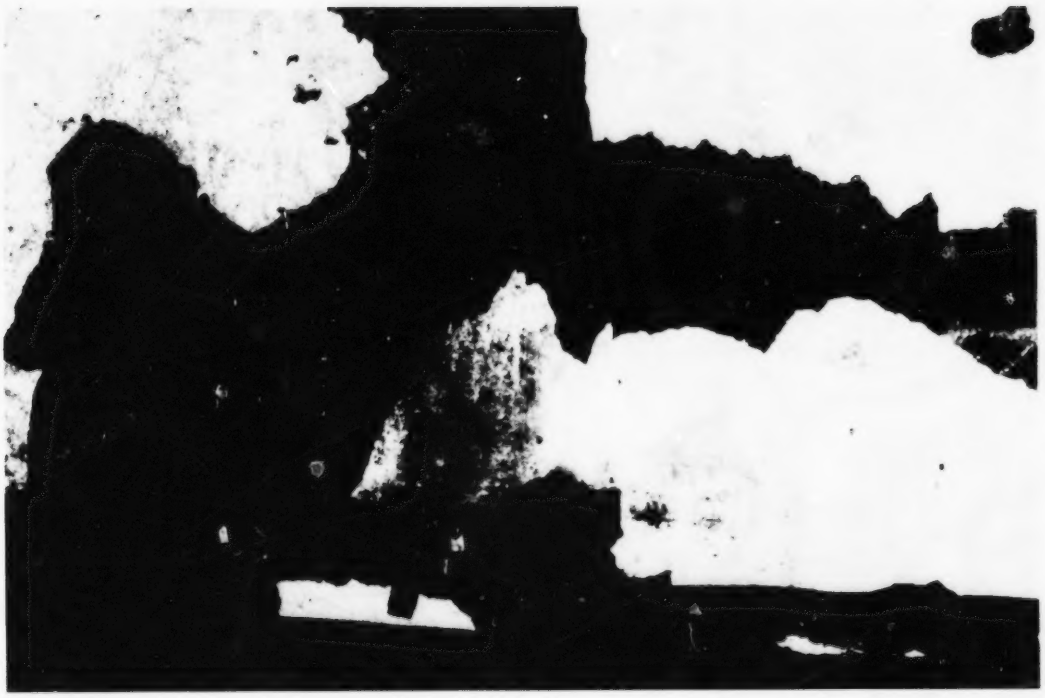
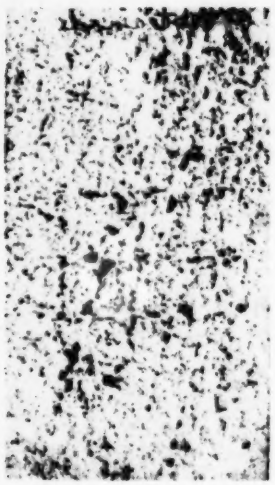


Figure A4/ Toronto Test Site. Close-up of Failure

Location: West face of beam, near second anode from south

East face of beam, half-way between anodes

Location: Pillar, near anode



Pillar, opposite anode

Figure A5/ Tape from Adhesion Tests at Toronto Site

Appendix B/ Fabrication of Concrete Samples and Electrification

The concrete samples were formulated to have a nominal strength of 30 MPa using a water/cement ratio of 0.4, 6% entrained air and a coarse aggregate size of 1/2". This mixture corresponded to the actual mixtures used at the test sites, except for the aggregate size which was reduced to be consistent with the thickness of the concrete samples. St. Lawrence Cement, high early strength type 30, was used. The mixing and pouring was done in 0.285 yd^3 batches in the University of Waterloo Concrete Laboratory.

The samples were allowed to cure in a humidity vault for 20 days and were removed for eight days before sandblasting with 400 micron silicon grit. After painting on the trowelled face of the panel, the edges and back were coated with an acrylic concrete sealer to provide a moisture barrier.

The samples which were not electrified did not contain reinforcing bar and measured 18" x 18" x 2". The samples which were electrified were poured on a 6" square grid of No. 5 steel reinforcing bar. The grid was a minimum of 1-1/2" from the trowelled surface. The final dimensions of each electrified panel were 18" x 18" x 4", with one side of each panel containing 5 lb/yd^3 (Cl^-) and the other side containing 12 lb/yd^3 (Cl^-). The first coat of paint was applied and let dry. Two platinum coated wires in parallel were applied towards the outside edges of the painted surface and secured by a fibre glass mesh tape. The second coat of conductive paint was applied over the tape, wire and initial paint to complete the anode connection. After the paint dried, a groove about 0.5" wide was ground through the paint along the middle of the panel in order to separate electrically the two sides of the concrete panel having the different chloride concentrations. The two wires were connected electrically to the positive terminal of a DC power supply and the reinforcing bar was connected to the negative terminal. The voltage was then adjusted to maintain the required current.

During the initial operation of the electrochemical cathodic protection system, the control panel indoors showed a sharp increase in the required voltage beyond what had been observed at the test sites. This increase was attributed to the panel drying in the low humidity. This panel was soaked in water for one day and sealed with the acrylic sealer. This procedure brought the voltage into the proper range.

Appendix C/ Adhesion Test Procedure

The adhesion test used was based on ASTM D 3359-78 entitled "Standard methods for measuring adhesion by tape test". This test involves scribing an X in the painted surface with a sharp blade and applying a strip of 3M brand adhesive tape, product number 710. This tape is then removed and the amount of paint left on the tape determines the rating. Since this test could also be used at the test sites, it was considered to be a useful and suitable test for adhesion.

In performing the test, some changes were made:

i) Tape number 710, which is 1" wide, was no longer available. Tape number 720 was obtained and used. It is believed to be of similar composition, but in a 2" width. The extra width may actually be easier to work with when dealing with large samples and structures.

ii) The tape did not adhere well to the paint under cool (5°C) or damp conditions. The test tapes shown in this report in Section 7 and in Appendix A were taken during moderately warm weather. At cooler temperatures, the adhesion was determined by the resistance of the paint at the scribed interface to attempts to flake off the paint manually with the knife.

iii) In order to increase the severity of the test, a cross hatch pattern was used before taping.

Appendix D/ Determination of Concrete Moisture Content

A search was carried out for an appropriate test to determine the moisture content of concrete. A number of tests were considered, including ASTM D 4263-83 and ASTM C 427, but each had serious limitations. For example, the condensate test ASTM D 4263-83 was not quantitative. This test would simply indicate the presence or absence of moisture in the concrete, but it was incapable of distinguishing variations in moisture content. Another method required a 6" deep well perpendicular to the drying surface(5), which would not be practical with our samples.

In order to develop a quantitative measurement of concrete moisture content, drying studies were carried out by monitoring the weight loss of a concrete sample measuring 6" x 2" x 2" when placed in a forced convection oven at elevated temperatures.

The weight changes with time at 150°C are shown in Figure D1. Most of the weight loss is seen to occur in the first six hours after which the weight appears to stabilize at a plateau value. The weight loss is 3.95% which can be considered the moisture content of the initial sample. In order to standardize the test, the moisture content was then assumed to be the weight loss of the sample after 24 hours at 150°C. Although this method cannot be reproduced at the sites, these moisture content values could be readily compared to any satisfactory on-site test which may be discovered or developed in the future.

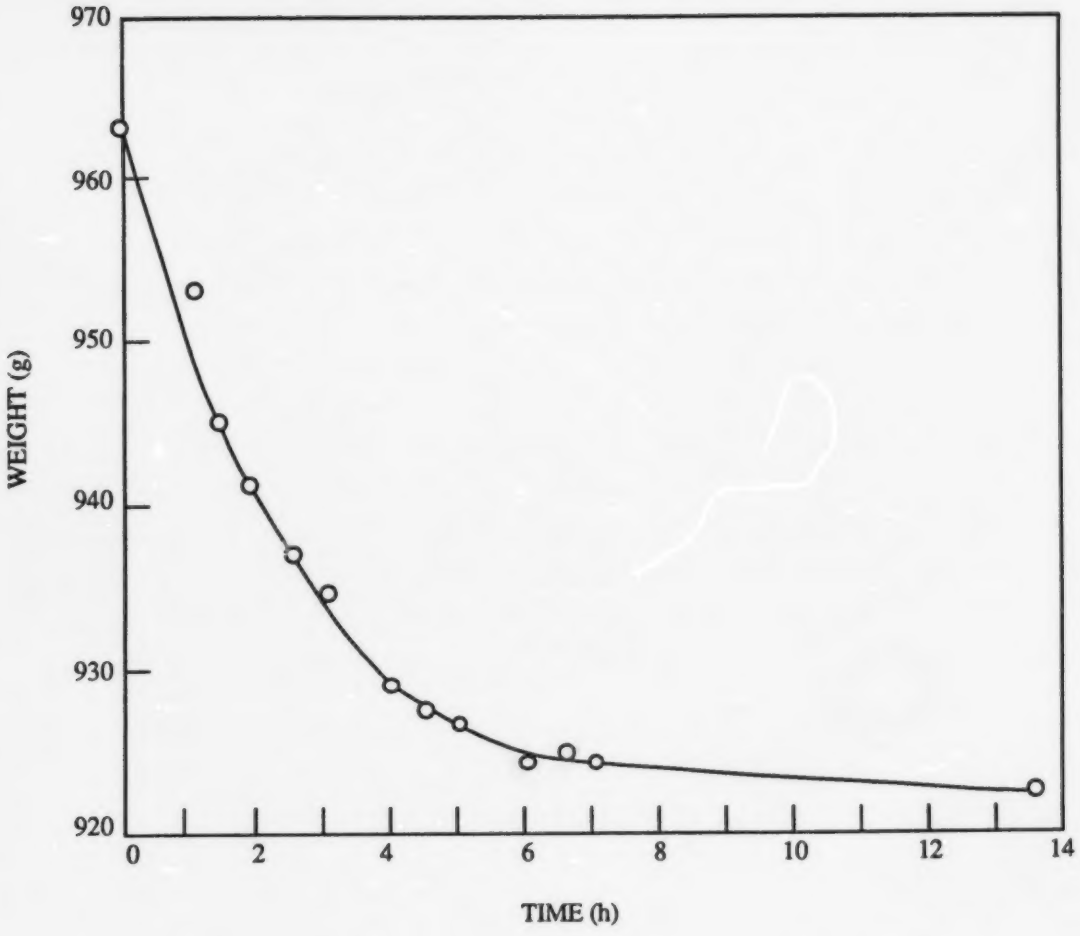


Figure D1/ Weight Loss of Concrete at 150° C, Concrete Sample Size 6" x 2" x 2"

Table D1/ Concrete Moisture Content

Environment	% Moisture
23°C, 30-50% R.H., 6 days	3.95
23°C, 30-50% R.H., 1 month	2.39
Laboratory Refrigerator, 5°C, 6 days	4.11
35-40°C, 30-50% R.H., 6 days	5.65
23°C, 55-85% R.H., 6 days	4.04
23°C, 100% R.H., 6 days	5.69
Outdoors, 1 month	5.15
Outdoors, 5 months	4.46
Outdoors, 5 months	4.99
Outdoors, 5 months	4.41

It is seen that the trends in the moisture content agree with what would be expected for the exposure conditions. Each value was determined from a separate sample. This procedure allows us to avoid assuming that the drying process is reversible, but it may lead to larger sample-to-sample variations. We did not determine reversibility of drying, that is whether a sample heated to dryness and then returned to its initial environment would recover its initial moisture content.

Appendix E/ Paint Morphology and Weatherability

The electrically conductive paint is a critical component in this system of cathodic protection. Deterioration of the paint in this application would lead to failure of the cathodic protection for the reinforced concrete.

Samples of weathered paint which had delaminated at the Toronto site appeared to be hard and brittle. Two main studies were made of the weathered paint in comparison with freshly dried paint - a thermogravimetric analysis of the two paints to indicate whether there had been a substantial change in the composition of the paint as a result of weathering, and a scanning electron microscopy study to indicate whether the morphology or internal structure of the paint had changed as a result of weathering.

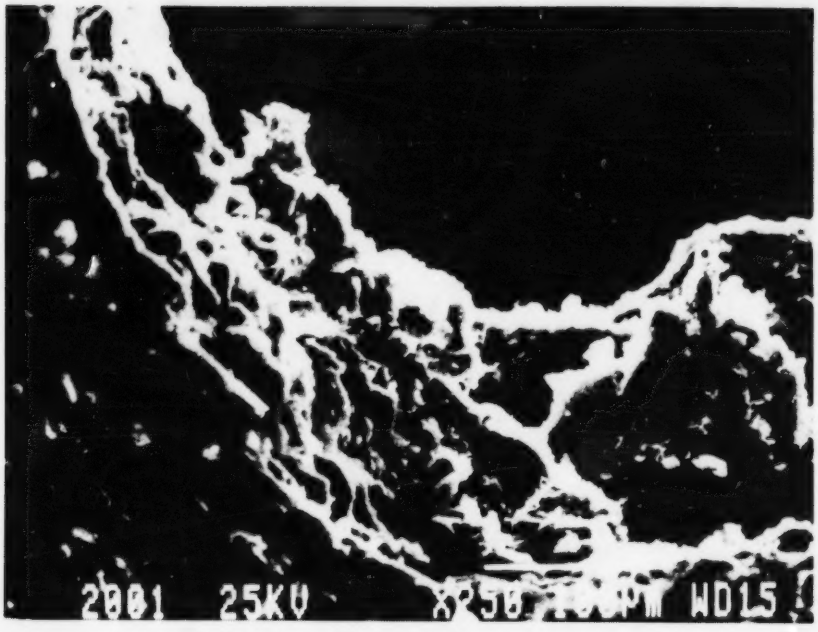
The procedure for thermogravimetric analysis consists of monitoring the weight of the sample while heating it according to a temperature program. In this case the old and new paints were heated from room temperature to 900°C in 15 minutes and held at 900°C for an additional 15 minutes in a Perkin-Elmer TGS-2 thermogravimetric system with a P-E System 4 programmer and data station. For both samples, weight loss began at 320°C and was substantially completed by 470°C. At 900°C, 80.2% of the old paint remained and 76.7% of the new paint remained. The weight loss was 19.3% for the old paint and 22.9% for the new paint.

The residue at 900°C is expected to be the graphite filler which does not burn at this temperature. This is a high level of filler which may be necessary to provide conductivity in the paint.

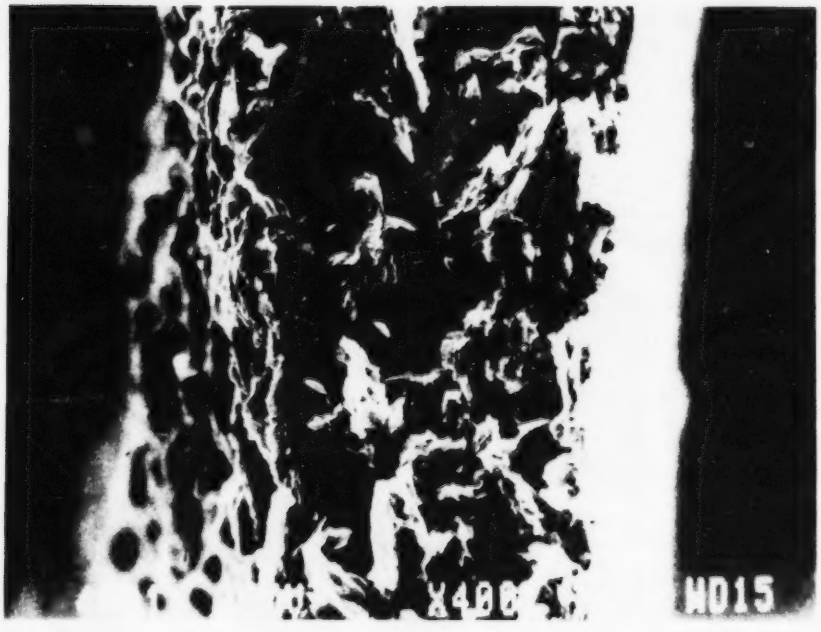
The weight losses of around 20% would represent the combustion of acrylic binder and any other organic materials which may be present. If the old paint had undergone severe deterioration upon weathering, a sizeable decrease in the content of binder would be expected. The decrease is only 3.6% by weight of the paint or approximately 15% by weight of the original binder. Some of this decrease could be attributed to solvents in the fresh paint which had not completely diffused out of the paint.

The brittleness which was observed in the weathered paint was also observed in the fresh paint. This brittleness could be attributed to the low level of binder and high level of filler in the paint.

Further insight into the nature of the paint was gained by examining the fracture surface of the paint by scanning electron microscopy. At moderate magnification in Figure E1, the old and new paints appear to be heterogeneous and porous. The roughness must be caused by irregularly shaped particles of graphite filler. Neither paint shows any change in morphology at either the outer or the inner surfaces, which indicates that the weathered paint is not deteriorating at either its exposed or its interfacial surfaces. An enlarged view of the interior morphologies of the paints in Figure E2 shows bridging between the graphite particles in each paint which does not seem to have been affected by weathering.

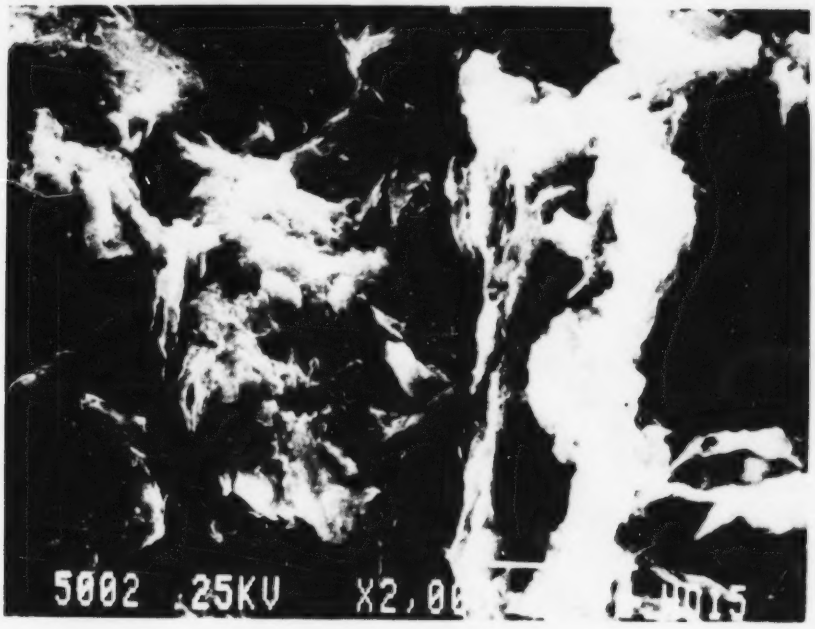


Cross-section of weathered paint at 250X

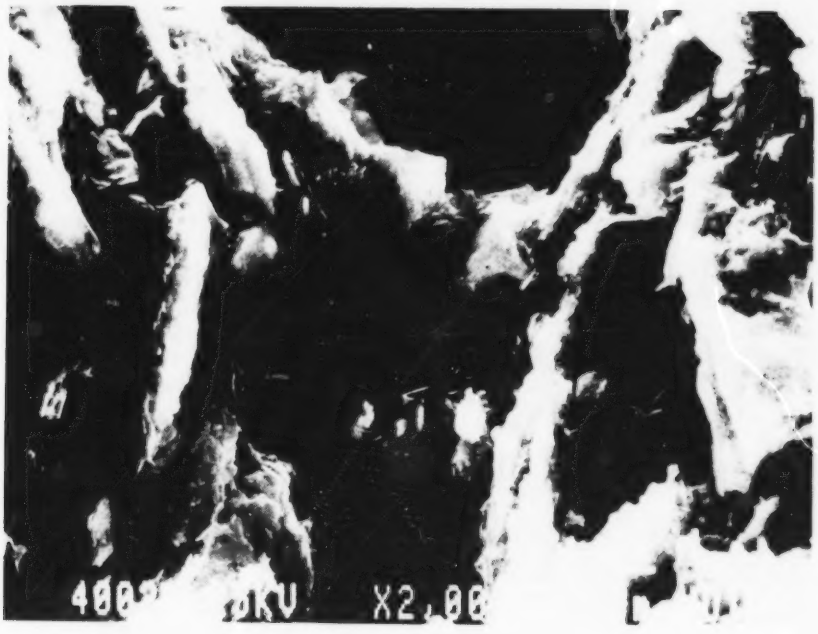


Cross-section of fresh paint at 400X

Figure E1/ Scanning Electron Micrograph of Weathered and Fresh Paints



Weathered paint at 2000X



Fresh paint at 2000X

Figure E2/ Scanning Electron Micrographs at Increased Magnification

Appendix F/ Determination of Concrete Acidity at the Interface

Since the failure of the painting system was observed to be occurring at the interface between the paint and the concrete, the acidity of the concrete directly below the paint was of interest. Various tests were attempted until the following test was developed which could be used at both site and laboratory locations.

A sample of the concrete surface to be tested was scraped into a 6 dram (about 5 mL) glass sample bottle. 1 mL of BDH Universal indicator, diluted according to directions, was added to the concrete and the mixture was shaken and swirled for 10 seconds. The concrete was allowed to settle and the colour of the supernatant liquid was compared to the colour scale provided by the manufacturer to arrive at an approximate pH value.

The pH of the concrete being poured was not measured in this study. The pH is usually considered to be about 10 to 11 when being poured and to increase to 12 or 13 upon setting due to the liberation of calcium hydroxide(6). In this test, the upper limit of pH values which can be detected by the universal indicator solution is 11. The sensitivity of the test is about 1 pH unit.

Table F1/ Acidity Values for Various Concrete Surfaces

	pH
Toronto site - south nose of beam	10-11
Toronto site - area of good adhesion	10-11
Toronto site - area of poor adhesion	10-11
Panel immersed before application	9.5-11
Laboratory control panel	9.5-11
Toronto panel, 4 mos	11
Toronto panel, 4 mos	10
Burlington panel, 4 mos	11
Burlington panel, 4 mos	11
Electrified, control, 5 lb/yd^3(Cl-)	10
Electrified, control, 12 lb/yd^3(Cl-)	11
Electrified, outdoors, 5 lb/yd^3(Cl-), 1mA/ft^2	9
Electrified, outdoors, 5 lb/yd^3(Cl-), 5mA/ft^2	9
Electrified, water pond, 12 lb/yd^3(Cl-), 5mA/ft^2	8.5
Electrified, brine pond, 5 lb/yd^3(Cl-), 5mA/ft^2	9
Electrified, brine pond, 12 lb/yd^3(Cl-), 1mA/ft^2	11
Electrified, brine pond, 5 lb/yd^3(Cl-), 5mA/ft^2	9
Electrified, brine pond, 12 lb/yd^3(Cl-), 5mA/ft^2	9

The outdoor site samples have been exposed to rains and weathering and the power had been turned off for a considerable length of time before the samples were taken. As a result, the samples may not be representative of the concrete condition when failure occurred at the test sites.

For samples prepared in this study, the painted concrete which did not fail showed pH values around 11, while the electrified painted concrete samples which fail showed pH values about 9, that is, the hydrogen ion concentration is about 100 times higher when failure occurred.

Appendix G/ Half-cell Potentials of Electrified Samples

An attempt was made to monitor the corrosion activity of the steel reinforcing bar by measuring the electrical half-cell of the reinforcing steel bar in concrete using ASTM test C 876-80. In this test a commercially available copper-copper sulphate half-cell of 1/4" diameter is placed in contact with the concrete surface freshly exposed by the removal of the paint. The positive terminal of a voltmeter is connected to the half-cell and the negative terminal of the voltmeter is connected to the terminal on the reinforcing steel bar. The power supply to the reinforced concrete panel is disconnected from the panel shortly before starting the test.

Table G1/ Half-cell Potentials Measured for Electrified Samples

Panel	(Cl-)	Current	V, at 2 mos	V, at 9 mos
Control	5	1	0.344	1.36-1.25
"	12	1	0.365	1.01-0.94
Outdoors	5	1	-	0.34-0.32
"	12	1	-	0.33-0.25
Outdoors	5	5	-	0.59-0.32
"	12	5	-	0.16-0.14
Water pond	5	1	0.520-0.436	1.21-0.86
"	12	1	0.476-0.340	0.90-0.78
Water pond	5	5	0.370	0.51-0.43
"	12	5	0.460	0.97-0.54
Brine pond	5	1	0.480	1.48-0.51
"	12	1	0.229	1.52-1.15
Brine pond	5	5	0.753	0.97-0.77
"	12	5	0.556	1.36-0.96

A great deal of difficulty was experienced in attempting to attain steady readings. Different half-cells were used, as well as different electrical junction devices and different electrical contact solutions between the half cell and the concrete surface.

These results appear very scattered. Comparing the half cell potentials with the adhesion results, it would appear that samples showing better adhesion have higher voltage readings. The voltmeter reading was observed to decrease with time as the reading was being taken.

These results do not appear to follow the qualitative behaviour mentioned in the ASTM test discussion. The ASTM guidelines state that for no corrosion to be occurring, the voltage should be less than 0.20V, while for corrosion to be occurring, the voltage should be greater than 0.35V. Between 0.20 and 0.35V, corrosion activity is uncertain. In this study, most of the half-cell potentials are observed to be above 0.35V. The only samples below 0.35V are the outdoors samples for which the paint system was observed to fail catastrophically. It appears that the half-cell potential measurements will have to be improved in method or in interpretation before they can be used in this type of study, since the test was not developed for an impressed current cathodic protection system.